

---

# Science with a 16m VLT: the case for variability of fundamental constants

Paolo Molaro<sup>1</sup>

INAF-OAT, Trieste Via G.B. Tiepolo 11, I 34143 Italy [molaro@oats.inaf.it](mailto:molaro@oats.inaf.it)

## 1 Abstract

Only astronomical observations can effectively probe in space-time the variability of the physical dimensionless constants such as the fine structure constant  $\alpha$  and proton-to-electron mass ratio,  $\mu$ , which are related to fundamental forces of nature. Several theories beyond the Standard Model (SM) allow fundamental constants to vary, but they cannot make quantitative predictions so that only laboratory experiments and astronomical observations can show if this is the case or set the allowed bounds. At the moment of writing there are claims for a variability of both  $\alpha$  and  $\mu$  at 5 and 4  $\sigma$  of C.L., respectively, although for  $\alpha$  they are contrasted by null results. The observations are challenging and a new spectrograph such as ESPRESSO at the combined incoherent focus of 4 VLT units (a potential 16 m equivalent telescope) will allow for a significant improvement in the precision measurement clearing up the controversy. If the variations will be confirmed, the implications are far reaching, revealing new physics beyond the SM and pointing a direction for GUTs theories. A most exciting possibility is that a variation of  $\alpha$  is induced by quintessence through its coupling with the electromagnetic field. If this is the case an accurate measurement of the variability could provide a way for reconstructing the equation of state of Dark Energy [1].

## 2 Introduction

The Standard Model (SM) of particle physics needs 26 dimensionless physical constants for the description of the natural world ([18]), of these few are directly related to the strength of fundamental forces. Among them the fine structure constant ( $\alpha = e^2/(\hbar c)$ ) and the proton-to-electron mass ratio, ( $\mu = m_p/m_e$ ) are of particular interest for us since they can be measured accurately by astronomical observations of intervening absorption systems towards distant QSOs. The fine structure constant  $\alpha$  is related to the strength

of the electromagnetic force;  $m_e$  is related to the vacuum expectation value of the Higgs field, namely the scale of the weak nuclear force, and  $m_p$  is related to the  $\Lambda_{QCD}$  or the strong nuclear force, therefore  $\mu$  is related to the ratio between the strong and weak nuclear forces.

A whatever small variability of these constants will produce a violation of the Weak Equivalence Principle (WEP) and would have far reaching implications revealing new physics beyond the Standard Model. In the Gev energy regime  $\alpha$  has already been shown to vary, but at low energies laboratory measurements with cooled atomic clocks failed to detect variations at the fifteen decimal place. The most stringent laboratory value is  $\dot{\alpha}/\alpha = (-2.7 \pm 3.9) \cdot 10^{-16} \text{ yr}^{-1}$  [14]. Astronomy is providing some evidence for both  $\alpha$  and  $\mu$  variations, although the evidence for  $\alpha$  has been contrasted by other groups. The astronomical claims for a variability are at the level of 6 ppm, part-per-million, and are measured up to redshift 4, or 12 Gyr lookback time. Several space-based missions as ACES,  $\mu$ SCOPE, STEP will soon improve existing laboratory bounds for WEP up to 6 orders of magnitude, and they should find violations if present claims of variability are correct under simple linear extrapolation. It is thus desirable that the astronomical community will be able to clear up the case before these accurate experiments will fly, but only astronomical observations can probe WEP non locally.

## 2.1 Why constants should vary?

Strings and multidimensional theories predict variable constants since the constants are defined in the whole multidimensional space and vary as extra dimensions are varying. The coupling between a scalar field with the electromagnetic field gives also varying constants. The required cosmological constant value is so small that a quintessence is a likely candidate for Dark Energy. Thus varying constants could provide insights into the nature of dark energy and provide evidence for scalar fields [10, 5]. Avelino et al. (2006) have shown how a precise detection of the variability of a constant could be used for the reconstruction of the quintessence potential and of the equation of state of Dark Energy [1].

If one constant is varying, then all the gauge and Yukawa couplings are also expected to vary. There is precise relation between the variation of  $\alpha$  and  $\mu$ , but it depends on the context the unification is realized in. Thus, simultaneous measurements of the variability of  $\alpha$  and  $\mu$  at similar redshift will be a key discriminant of the several GUTs models [4]. Theoretical preferences are for a relative change between the  $\mu$  and  $\alpha$  variations of  $\leq 50$ , but larger values are also possible, implying that the strong-coupling constant is running faster than  $\alpha$  and therefore  $\delta\mu$  should be found to be larger then  $\delta\alpha$ .

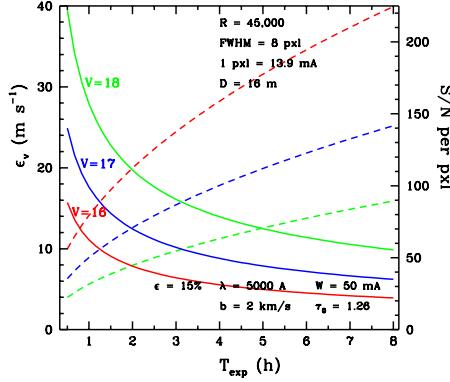
### 3 The observations

Observations of the Werner and Lyman series of the molecular hydrogen in Damped Ly $\alpha$  galaxies (DLA) can be used to bound  $\mu$  variations. The electron-vibro-rotational transitions have different dependence from the reduced mass and can be used to constrain a variability of  $\mu$ . UVES observations of the DLA at  $z_{abs} = 3.0$  towards QSO 0347-383 [6], but see [7], and of the DLA towards QSO 0405-443 have provided  $\delta\mu = (24 \pm 6)$  ppm, when the two systems are combined together [16]. The handful of systems investigated for this purpose reflects the difficulties of the measurement. There are few DLA showing H<sub>2</sub> and the restframe H<sub>2</sub> lines are at  $\approx 1000$  Å, falling in the Lyman forest and requiring a  $z_{abs} \geq 2$  to be redshifted into the optical window. H<sub>2</sub> systems are extensively searched at the moment so that probably new observations will be available in the near future to verify these first findings.

Fine structure variability can be probed in the early universe through the primordial nucleosynthesis or through the CMB power spectrum but at the level of a few percent. The most effective way has been achieved through the analysis of metal lines of intervening absorption systems observed in the spectra of distant QSOs. The energy levels of high mass nucleus are subject to relativistic corrections which are sensitive to the mass number. These have been calculated for the most frequently observed resonance lines and constitute the popular Many-Multiplet method. Murphy and collaborators [11] by comparing the redshift of several lines in a sample of 143 systems in the redshift interval  $0.2 < z_{abs} < 4.2$  found evidence for  $\Delta\alpha/\alpha = (-5.7 \pm 1.1)$  ppm. However, this evidence has been contrasted by two other groups which did not find evidence for variability at the level claimed. Chand et al. found an average value of  $(-0.6 \pm 0.6)$  ppm in a sample of 23 systems, while Levshakov and collaborators found  $(-0.12 \pm 1.79)$  ppm and  $(5.66 \pm 2.67)$  ppm in two systems at  $z = 1.15$  and  $1.84$ , respectively, and by using lines of Fe II only [15, 8]. What is the best methodology is currently under debate [13, 12, 17, 9].

#### 3.1 Would you like an ESPRESSO?

These observations are challenging the instrumental performances of UVES-VLT or HIRES-Keck telescopes. Measuring the variability of  $\mu$  or  $\alpha$  implies the measurement of a tiny variation of the position of one or few lines with respect to other reference lines. It is not much different than revealing exoplanets, but with the limitations that only few lines can be used and QSO are much fainter than stellar sources. The precision in the measure of a line position increases with the spectrograph resolving power till the intrinsic broadening of the metal lines is resolved, the signal-to-noise and with the decreasing of the pixel size ( $\Delta\lambda^{3/2}$ , see [2] for a precise relation). The ESPRESSO spectrograph described by L. Pasquini at this conference, both in the *Super-HARPS* or *Super-UVES* modes, holds the promise for one order of magnitude improvement compared to what presently achieved. Fig. 1 shows the accuracy



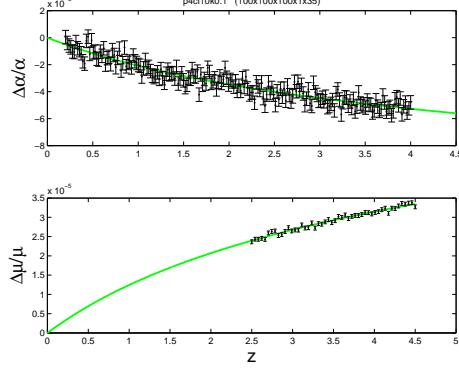
**Fig. 1.** Estimated accuracy in the position of an absorption line with  $\text{EW} = 0.050$  Å and  $b = 2 \text{ km s}^{-1}$  as a function of the exposure time for ESPRESSO@4UT. On the figure legend other instrumental and observational parameters are given.

which can be achieved in the photon limit approximation and accuracies of few  $10 \text{ ms}^{-1}$  are reachable for single lines with relatively short exposures even for faint sources. An error of  $30 \text{ m s}^{-1}$  corresponds to an error of 1 ppm for  $\alpha$ ; such an accuracy will be enough to resolve the present controversy and establish in a definitive way whether  $\alpha$  or  $\mu$  are varying as claimed. However, one important requirement is the improvement of the wavelength calibration, for instance with the LaserComb as discussed here by A. Manescu.

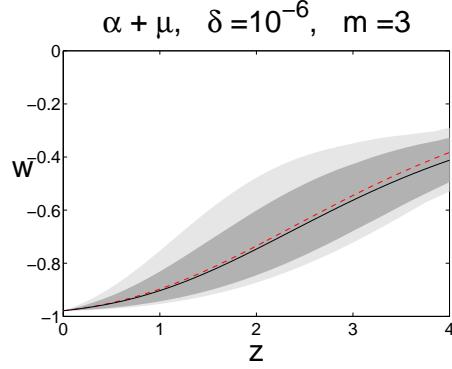
#### 4 Constants and Dark Energy

Avelino and collaborators [1] have shown that the measurement of the behaviour of variations in  $\alpha$  and  $\mu$  with redshift can be used to infer the evolution of the scalar field and of the equation of state of the Dark Energy, not very differently from the reconstruction of the potential from the motion of a particle. Nelson Nunes kindly adapted their detailed analysis to a realistic set of observations which can be performed with ESPRESSO@4VLT. It is assumed that it has been possible to measure  $\alpha$  and  $\mu$  for a sample of 200 and 25 systems respectively and with an equal, for simplicity, accuracy of 1 ppm. In the example case the scalar potential is taken as  $V(\phi) = V_0(\exp(10k\phi) + \exp(0.1k\phi))$ , which is one of the simplest possible potential accounting for the accelerated expansion. Fig. 2 shows the Monte Carlo redshift distribution of the data with this scalar potential assuming that the variation of  $\alpha$  is -5 ppm at  $z=3$  and that the two constants are mutually linked by a fix ratio of -6, as it is suggested by some of the observations. In Fig. 3 the red dotted line shows the assumed behaviour of the  $w(z)$  while the black continuous line shows its recovering through a fitting of the simulated data points with a polynomial of order  $m=3$  (cfr [1] for details). The shaded regions show the 1 and 2 CL of the

reconstruction, when both  $\alpha$  and  $\mu$  measurements have been considered. We emphasize that only few observations would clearly show if  $w(z)$  is an evolving function of  $z$ .



**Fig. 2.** Monte Carlo data set based on redshift dependence of the scalar potential given in the text producing a  $\Delta\alpha/\alpha = -5$  ppm at  $z=3$ . Error bars are of 1 ppm for  $\alpha$  and  $\mu$  as expected with ESPRESSO@4VLT.



**Fig. 3.** Reconstruction of the equation of state and its error band. Dashed line represents the assumed dark energy and the solid line the reconstruction's best fit. Shaded regions show the 1 and 2 CL of the reconstruction

## 5 Conclusions

Variability of physical constants is an important issue for physics and only astronomy can probe this possibility for  $\alpha$  and  $\mu$  in the full space-time. Present

observations provide hints of variation for both constants but those for  $\alpha$  have been contrasted by other investigations. The ESPRESSO spectrograph presently conceived for the incoherent combined focus of the 4VLT would improve present accuracy by a significant factor and therefore clarify the case. A confirmation of the variability would have far reaching implications revealing new physics beyond the SM, showing the right path for GUTs and possibly providing insights into the nature of Dark Energy. If no variability is found, then the new more stringent bounds will be usefully combined with local space experiments for WEP violation. Overall, this seems to be a great opportunity for the astronomical community and I hope that ESO will take advantage of it by considering the construction of the new high precision spectrograph at the incoherent combined focus of the 4 VLT units, a  $\approx 16$ m equivalent telescope.

## 6 Acknowledgements

It is a pleasure to thank N. Nunes for adapting his simulations for ESPRESSO, all the ESPRESSO collaboration, in particular S. Levshakov and M. Murphy.

## References

1. Avelino P., Martins, C. J. A. P., Nunes, N. J., & Olive, K. A., Phys. Rev. D **74**, 083508, (2006)
2. Bohlin R. C., Jenkins, E. B., Spitzer, L., Jr., et al ApJS **51**, 277, (1983)
3. Chand, H., Srianand, R., Petitjean, P., & Aracil, B., A&A **417**, 853, (2004)
4. Dent, T. in *Astrophysics, Clocks and Fundamental Constants*, eds. S. G. Karshenboim and E. Peik (Springer-Verlag, Berlin, (2007)
5. Fujii, Y., arXiv: astro-ph/0709.2211, (2007)
6. Ivanchik, A., Petitjean, P., Varshalovich, D. A., Aracil, D., Srianand, R., Chand, H., Ledoux, C., & Boisse, P., A&A **440**, 45, (2005)
7. Levshakov S.A., Dessauges-Zavadsky, M., D'Odorico, S., & Molaro, P., MNRAS **333**, 373 (2002)
8. Levshakov, S. A., Molaro, P., Lopez, S. et al., A&A **466**, 1077, (2007)
9. Molaro, P., Reimers, D., Agafonova I.I., & Levshakov, S. A., in *Astrophysics, Clocks and Fundamental Constants*, eds. S. G. Karshenboim and E. Peik (Springer-Verlag, Berlin) astro-ph/0712.4380 (2007)
10. Martins, C. J., A. P., astro-ph/0610665, (2007)
11. Murphy, M. T., Flambaum, V. V., Webb, J. K., et al.. Lecture Notes Phys., **648**, 131 (2004)
12. Murphy, M. T., Webb, J. K., & Flambaum, V. V., astro-ph/0708.3677 (2007);
13. Murphy, M. T., Webb, J. K., & Flambaum, V. V., MNRAS in press astro-ph/0612407 (2007)
14. Peik, E., Lipphardt, B., Schnatz, H., et al. arXiv: physics/0611088 (2006)
15. Quast, R., Reimers, D., & Levshakov, S. A., A&A **415**, L7, (2004)
16. Reinhold E., Buning, R., et al., Phys. Rev. Lettr **96**, 151101 (2006)
17. Srianand, R., Chand, H., Petitjean, P., & Aracil, B., arXiv:0711.1742 (2007)
18. Tegmark M. Águirre, A., Rees, M., & Wilczek, F. Phys. Rev. D. **73**, 023505 (2006)